Fundamentals to Engineer Resilient Systems

How Human Adaptive Systems Fail and The Quest for Polycentric Control Architectures

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"Even if the world were perfect, it wouldn't be."
Yogi Berra

"Anomalies are what happens when something else was planned; whatever the plan, something else always happens."

Resilient Control Systems

R[CS]
~ modulating adaptive capacities

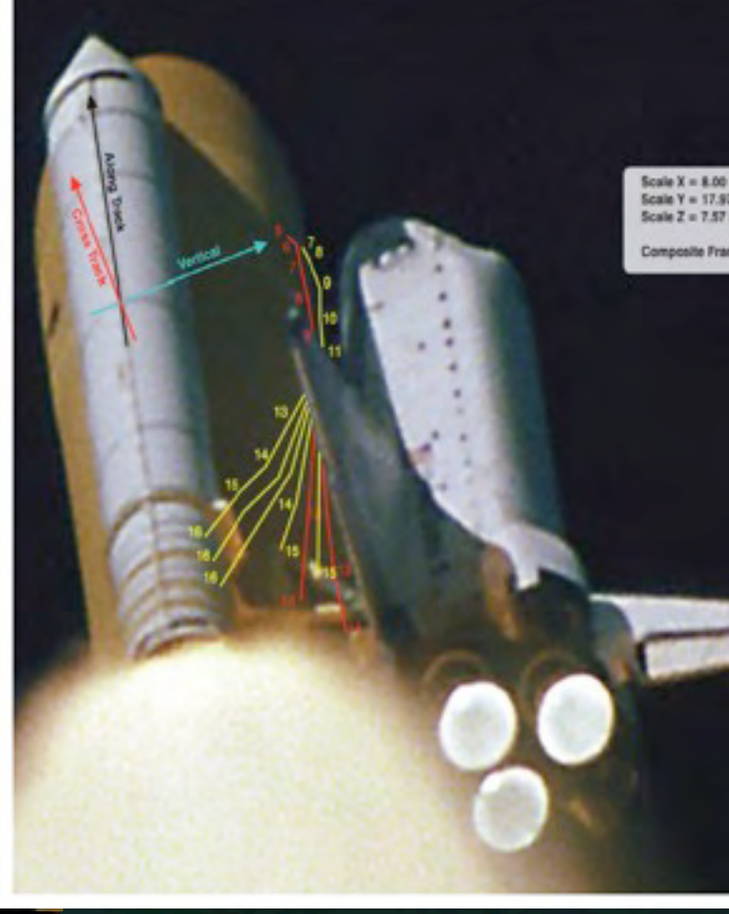
~ multi-echelon, distributed, human-technology

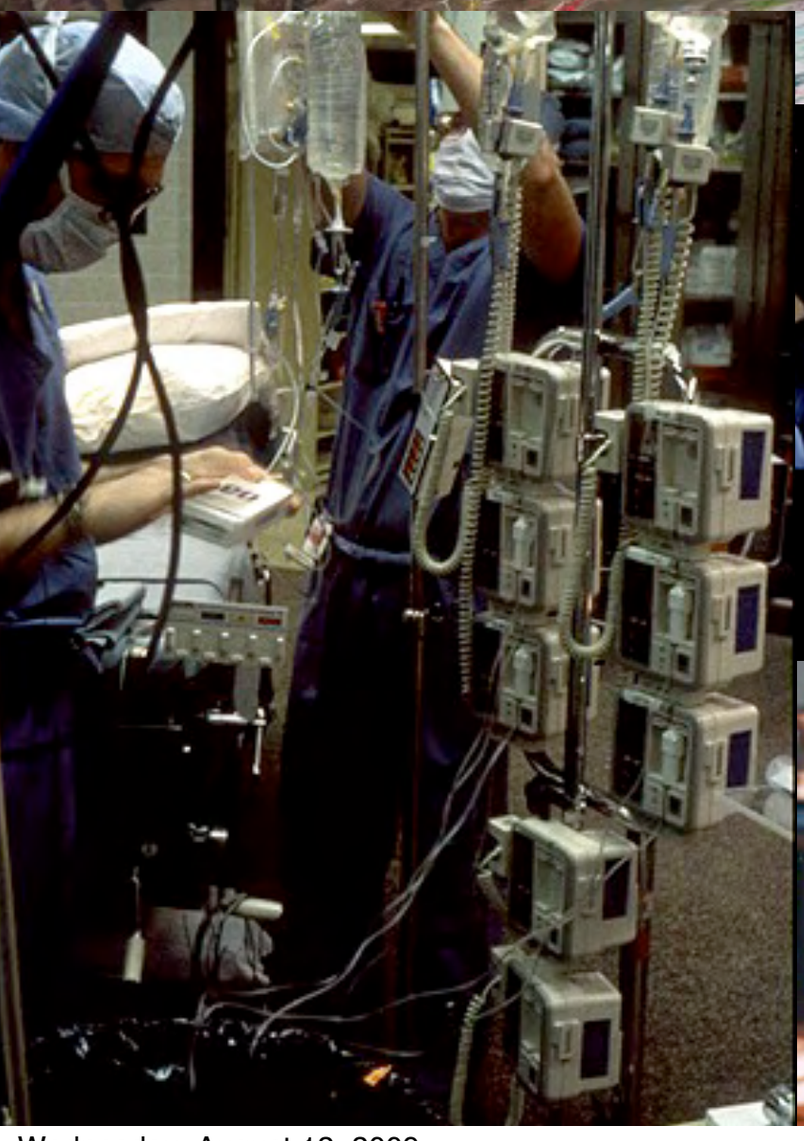
[RC]S
drivers: scale changes, coupling

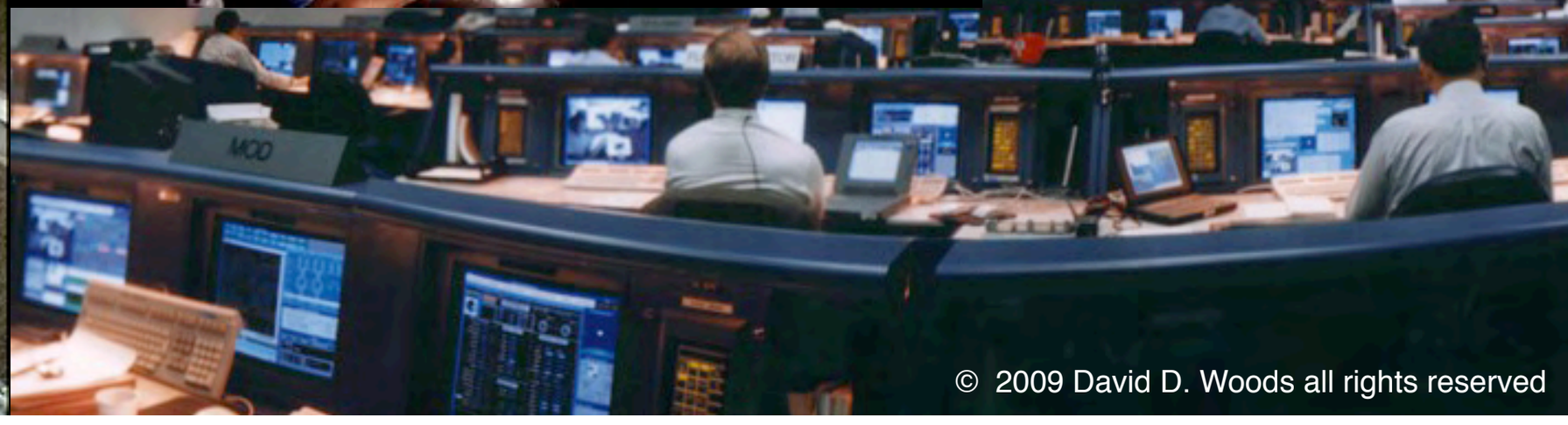
~ sensing/networking/robotic technologies extend perception/action over wider scales,

~ connectivity revolution extends interdependent activities (coupling)

Human Systems







Human systems, simultaneously are

~ adaptive systems,
~ cognitive systems,
~ distributed systems,
~ human-machine systems,
~ purposive systems,
~ multi-level systems, and
~ co-adaptive systems.

Joint Activity:

~ distributed over multi-echelon network of interdependent human-machine roles
~ meeting critical system goals depend on the joint impact of the actions and decisions of multiple parties over time

At some level of analysis systems are human systems as people create, operate, and modify that system for human purposes, and as people, not machines, gain or suffer from the operation of that system.

Human Systems as adaptive, goal directed, meaning seeking, explanation generating, attention focusing, learning agents

New technology provides resources that stimulate people to adapt, to re-design:

- Expansive adaptations where leaders exploit new capabilities to transform activity, coupling, & work in order to meet pressing goals.

E-ICU nurses asked to track billable events
New policy following success of telemedicine system 2008

- Gap-filling adaptations to work around complexities when designs introduce various kinds of bottlenecks in ongoing activities.

Turn it off below 10,000 ft.
Airline automation policy circa 1995

easy to see a person or a piece of technology
easy to see components, rules
easy to see things

hard to see expertise

harder to see interactions, coordination, synchronization

harder yet to see adaptation, complexity, brittleness, resilience

easy to mistakenly—
    juxtapose people versus machines,
    see erratic human behavior,
    regulate components
when co-adaptive dynamics are the underlying drivers

shift design focus to interventions that
leverage human adaptability rather than
increasing capability of isolated machines

The Potential for Future Adaptive Action

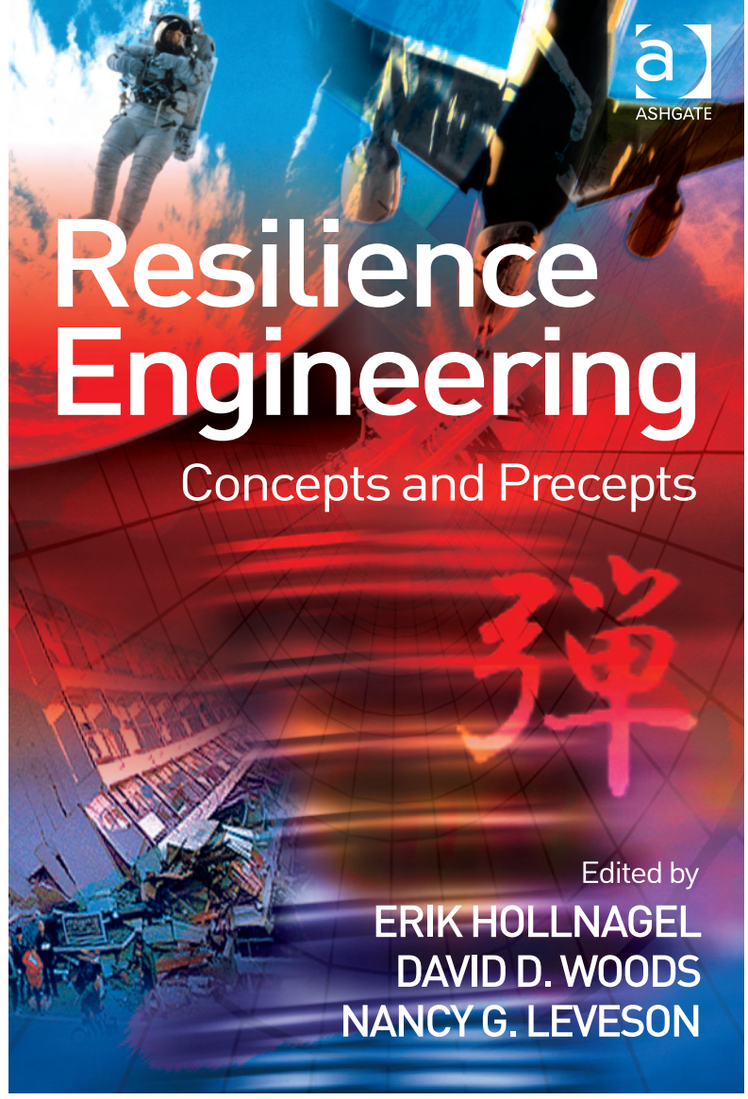
How change expands or constricts adaptive capacities

Adaptive capacity is future oriented -- what and how the unit could stretch in the future.

Increasingly brittle systems

Analyze how the unit has adapted to past disrupting events

Means to enhance resilience in face of surprise



First Principles:

- distinguish *first* and *second* order adaptive capacity

  potential for action in the future when conditions change or new events challenge old models, ...

- optimality - brittleness tradeoff (Doyle)
  - ~ acute-chronic
  - ~ specialist-generalist
  - ~ efficiency-thoroughness (Hollnagel)

- cross-level interactions
  - ~ polycentric

- multiple perspectives
  - ~ reflective
  - ~ calibration

Balancing
Specialized/General
Acute/Chronic
Efficient/Thorough
Production/Safety

- NASA's FBC failures
- Stories of Sacrifice decisions
- Help organizations decide when to relax production pressure to reduce risks
- Extra investment in safety is most needed when least affordable

Creating Safety Under Pressure

d f(S)

NASA in a changing environment under performance demands and resource pressures:

- Drive down the cost of launch
- Shorter, aggressive mission schedules
- New partners and relationships
- New roles
- Skill erosion
- Heightened public interest

"Risk, therefore, becomes the "fourth dimension" of project management—treated equally as important as cost and schedule."

A common expression from military decision making:

No plan survives contact with a disaster-in-the-making.

… our experience [is] that every response is totally different and causes unforeseen problems or opportunities. We have never gone to an actual response and used the equipment the way we thought we would. (Murphy & Burke, 2005, p. 4)

How to be Prepared to be Surprised?

Potential for surprise is related to
- the next anomaly or event that practitioners will experience and
- how that next event will challenge pre-developed plans and algorithms in smaller or larger ways.

To assess potential for surprise in a setting, ask how the above generalization applies?
- *how do plans survive or fail to survive contact with events*?
- search for the kinds of situations and factors that challenge the textbook competence envelope

Mis-Calibration
organization is operating more precariously than it realizes

Organizations can
~ mis-estimate their adaptive capacity
~ overconfident that they know it precisely

Resilient Organizations
~ acknowledge uncertainties and change
~ struggle to update and re-calibrate
~ support sacrifice judgments—contexts to relax acute goals to serve chronic goals

requires
~ perspective shifts/contrasts
~ managing appropriate skepticism
~ balancing the 4 l's across echelons: independent, involved, informed and informative

Radical Implications:

Simultaneously, all human adaptive systems are

- well - adapted
  - ~ fluency law: Well-adapted activity occurs with a facility that belies the difficulty of the demands resolved and the dilemmas balanced
- under - adapted
  - ~ pressures from stakeholders (e.g. FBC pressure)
  - ~ law of stretched systems
- mal - adapted
  - ~ tradeoffs
  - ~ reflective
  - ~ calibration

Struggle for fitness is ongoing

Sample 1 of Resilience

Shortly before surgery, an attending anesthesiologist comes to understand that the surgical plan expects a relatively short procedure with little blood loss. However, the attending recognizes that given this patient's other problems, it will be difficult to establish access quickly if significant fluid replacement is needed to manage cardiovascular physiology. Furthermore, the anesthesiologist recognizes that, while the surgical plan represents a typical surgical course, in this context the procedure could go much longer and blood loss could be much greater than expected. As a result, the attending instructs the resident to place more lines than normal when the patient is being prepped for surgery. This will allow the attending to respond quickly with fluid replacement should any challenges to cardiovascular physiology occur during surgery.

Sample 2 of Resilience

Anesthesiology has become much safer over the last 15 years. In addition, there have been changes in medical practice that allow for/ encourage surgeries to occur in outpatient settings (e.g., cosmetic surgery). As a result, anaesthesia practice has migrated away from the traditional operating room setting where there are a variety of technological and human resources that can be called on should a crisis occur. The safety manager for the health care network recognizes that moving more anaesthesia practice to outpatient settings increases brittleness, that is, should an unexpected event trigger a crisis, less expertise, experience, and equipment is available to manage the situation. The safety manager initiates a new crisis management training program for outpatient surgery teams that allows personnel to practice how to respond to a crisis including how to find and bring additional expert resources into the different locations where a crisis could occur.

Patterns of Adaptive Breakdown - Mal-Adapted

1. Decompensation: exhausting capacity to adapt as disturbances/challenges cascade.

2. Working at cross-purposes: behavior that is locally adaptive, but globally maladaptive

3. Getting stuck in outdated behaviors: the world changes but the system remains stuck in what were previously adaptive strategies.

Patterns of Adaptive Breakdown

1. *Decompensation:*
breakdown occurs when challenges grow and cascade faster than responses can be decided on and deployed to effect.
  Sub-patterns: eg,
    - Falling behind tempo
    - Inability to transition to new modes of functioning

2. *Working at cross-purposes*:
~ inability to coordinate different groups at different echelons as goals conflict.
  Sub-patterns (horizontal and vertical): eg,
    - Tragedy of the commons
    - Fragmentation (stuck in silos).
    - Missing side effects of change (temporal)

3. *Getting stuck in outdated behaviors*:
  Sub-patterns: eg,
    - Oversimplifications
    - Fixation
    - Distancing through differencing
    - Cook's Cycle of Error

1. Decompensation

breakdown occurs when challenges grow and cascade faster than responses can be decided on and deployed to effect.

~ Starling curve cardiology (Feltovich)

~ cardiovascular anesthesiology (Cook)

~ asymmetric lift, aviation automation, bumpy transfer of control (Sarter & Woods)

~ 'surge' capacity in ER (Wears)

~ ICU bedmeister and crunches (Cook)

~ Tempo of operations & bottlenecks

Box 1 Example of a case of "going solid"

Setting
A large tertiary care facility in a major metropolitan area in the United States.

Event
Near the end of a routine scheduled surgical procedure on patient A, the circulating nurse called the recovery room in anticipation of bringing the patient to it. The recovery room placed the transfer from the operating room "on hold" because all the recovery room locations were filled by patients. Among these was patient B who should have been transferred from the operating room directly to an intensive care unit (ICU) bed. Patient B was in the recovery room because there was no ICU bed available. Investigation of the circumstances revealed that the ICU bed was occupied by patient C whose condition would allow transfer to the regular ward but the regular ward bed was occupied by patient D who was ready for discharge but was awaiting arrival of a family member to transport him to his home. Bed occupancy within the hospital had been at saturation for both ICU and regular ward beds for several weeks.

The high occupancy situation was managed by nurses and administrators by pairing new postoperative admissions with anticipated patient discharges, matching expected discharge and expected end of surgery times. Senior hospital management became involved in moment to moment decision making about bed allocation, surgical procedures starts, and intra-hospital patient transfers. Managers also sought increased efficiency of resource use, mainly through direct inquiries about patient status. A new administrative nursing position was established to centralize and rationalize bed resources. The system remained solid for approximately 5 weeks.

From Cook and Rasmussen 2005

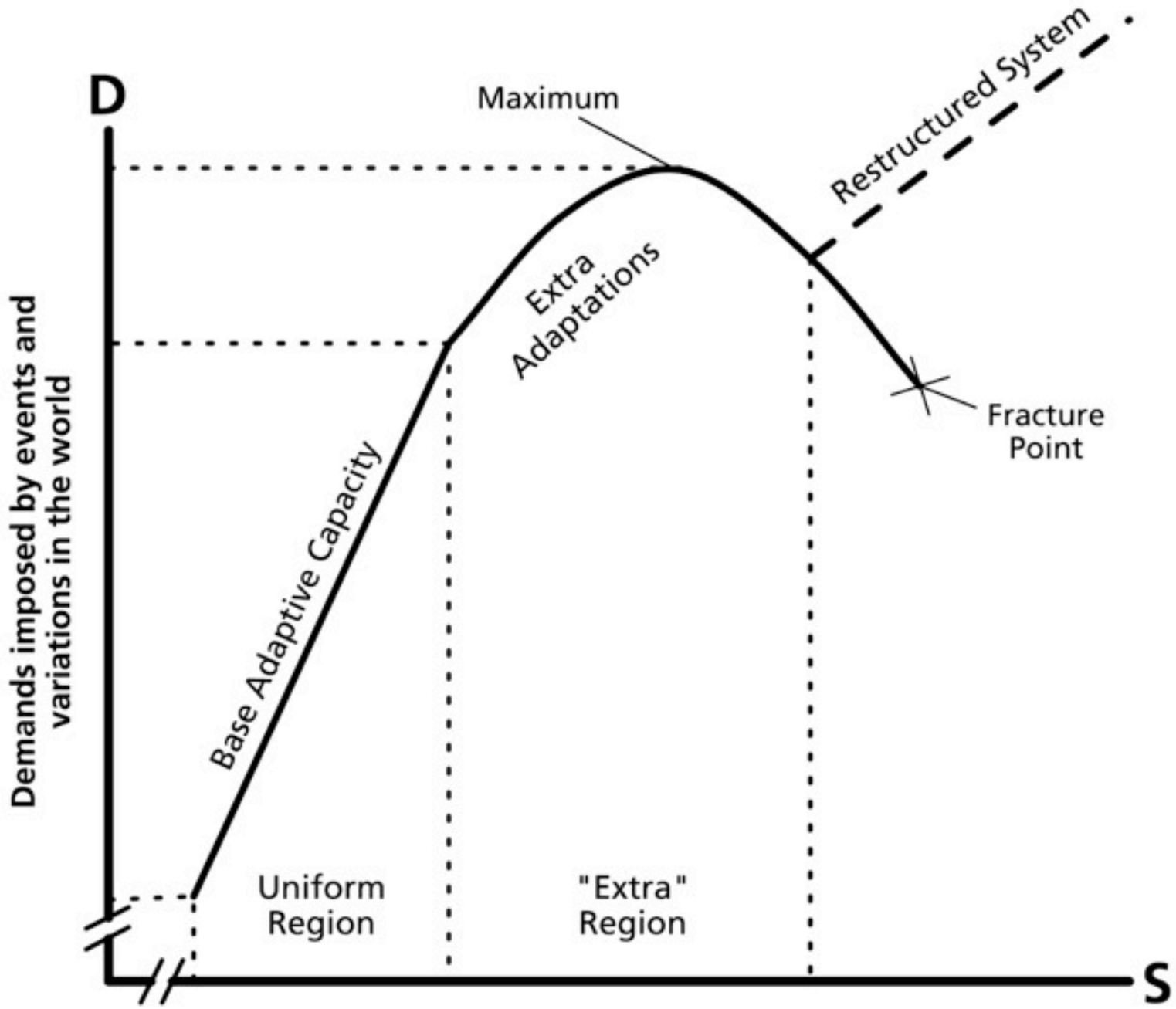
Cardiovascular anesthesia

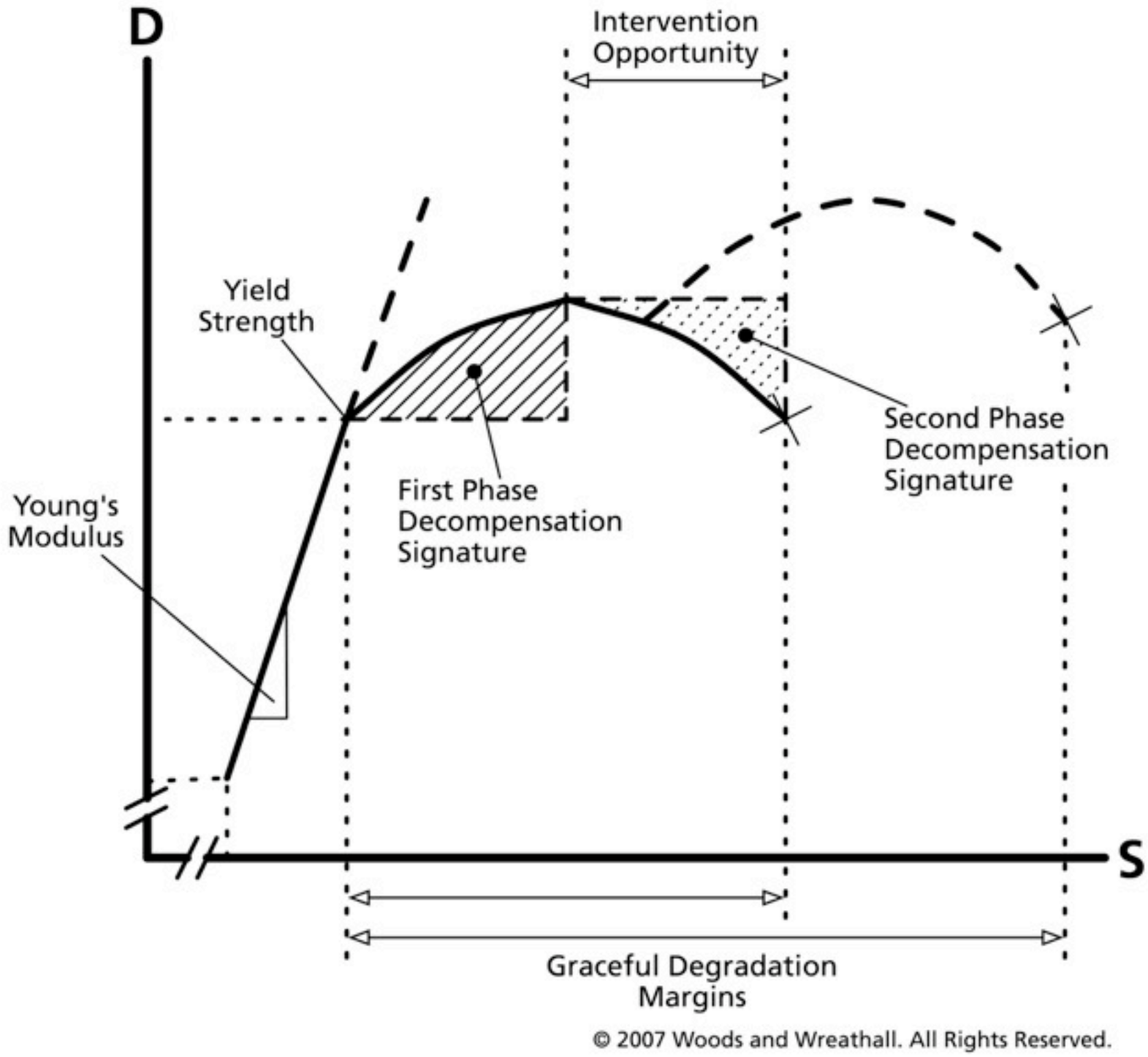
Cook, Woods, McDonald, 1981

An elderly patient presented with a painful, pulseless, blue arm indicating a blood clot in one of the major arteries that threatened loss of that limb. The patient medical history includes high blood pressure, diabetes requiring regular insulin treatment, a prior heart attack and previous coronary artery bypass surgery. The patient also had evidence of recently worsening congestive heart failure, i.e., shortness of breath, dyspnea on exertion and leg swelling (pedal edema). Electrocardiogram (ECG) changes included inverted T waves. Chest x-ray suggested pulmonary edema. The arterial blood gas (ABG) showed markedly low oxygen in the arterial blood (PaO2 of 56 on unknown FiO2). The blood glucose was high, 800. The patient received furosemide (a diuretic) and 12 units of insulin in the emergency room.

The patient was taken to the operating room for removal of the clot under local anesthesia with sedation provided by the anesthetist. In the operating room the patient's blood pressure was high, 210/120; a nitroglycerine drip was started and increased in an effort to reduce the blood pressure. The arterial oxygen saturation (SaO2) was 88% on nasal cannula and did not improve with a rebreathing mask, but rose to the high 90s when the anesthesia machine circuit was used to supply 100% oxygen by mask. The patient did not complain of chest pain but did complain of epigastric pain and received morphine for pain. Urine output was high in the operating room. The blood pressure continued about 200/100. Nifedipine was given sublingually and the pressure fell over ten minutes to 90 systolic. The nitroglycerine was decreased and the pressure rose to 140. The embolectomy was successful. Postoperative cardiac enzyme studies showed a peak about 12 hours after the surgical procedure indicating that the patient had suffered a heart attack sometime in the period including the time in the emergency room and the operating room. The patient survived.

This man was in major sort of hyperglycemia and with popping in extra Lasix [furosemide] you have a risk of hypovolemia from that situation. I don't understand why that was quietly passed over, I mean that was a major emergency in itself . . .





Emergency Medicine

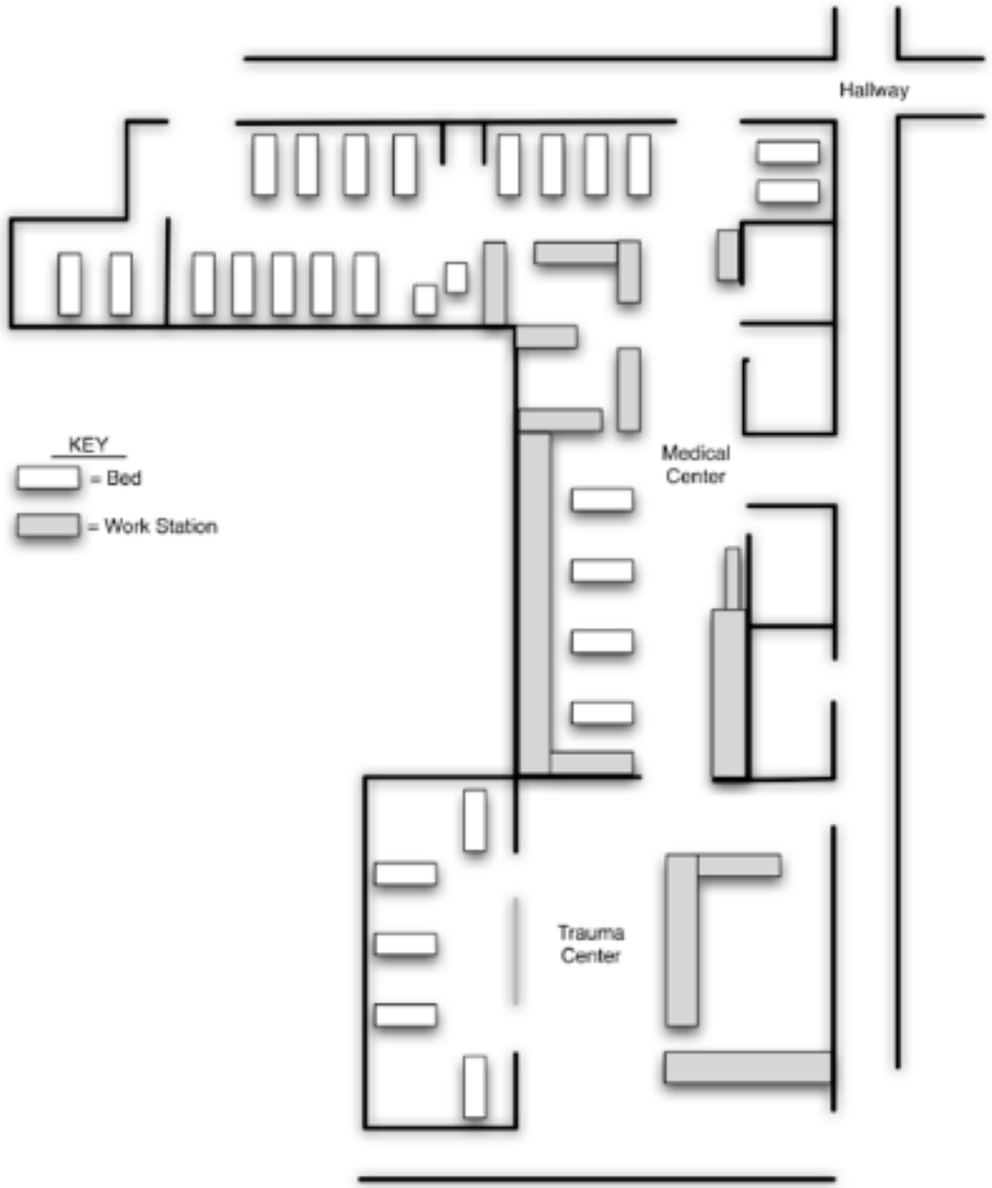
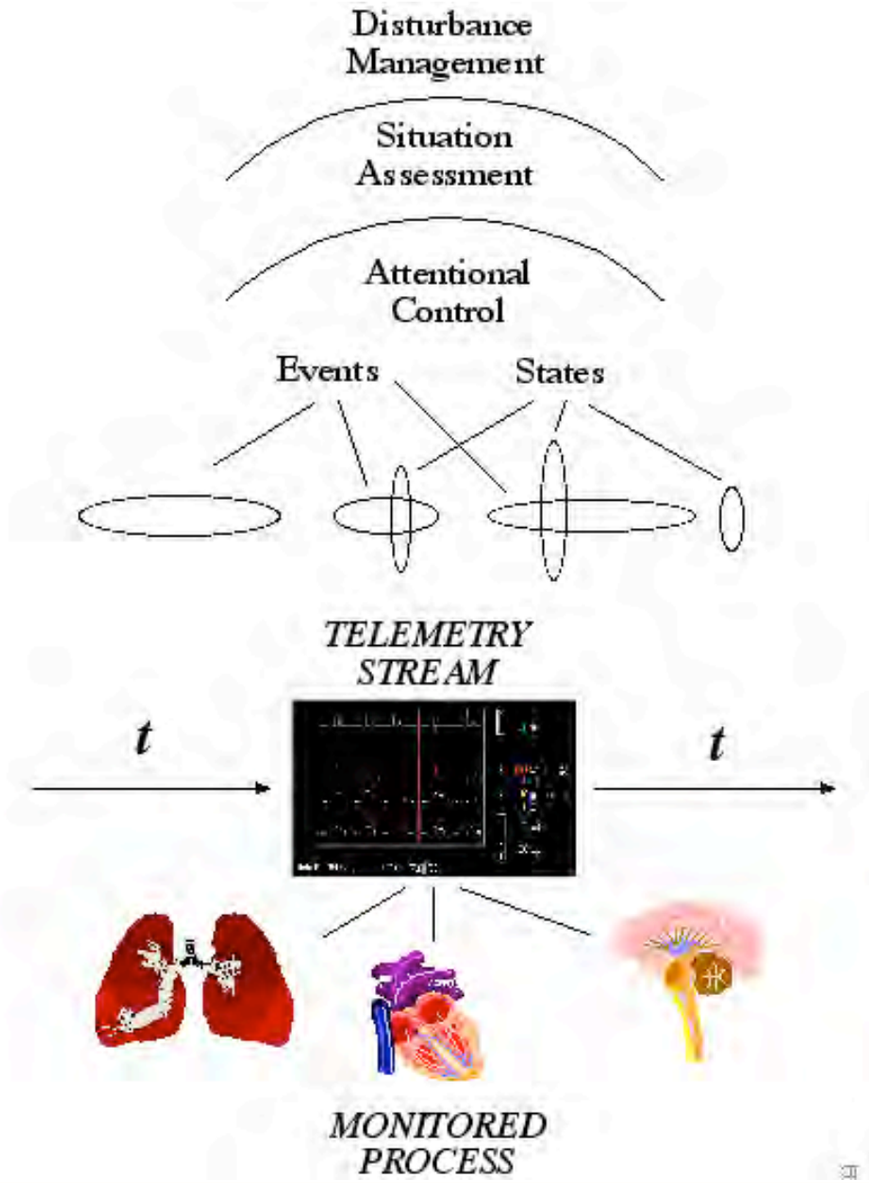


Figure 1. Schematic layout of the two units involved in these events.



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2. Working at cross-purposes: behavior that is locally adaptive, but globally maladaptive

~ inability to coordinate different groups at different echelons as goals interact and could conflict.

sub-patterns (horizontal and vertical):

- Tragedy of the commons
- Fragmentation (stuck in silos).
- Missing side effects of change (temporal)
- Failure to resynchronize
- Double Binds

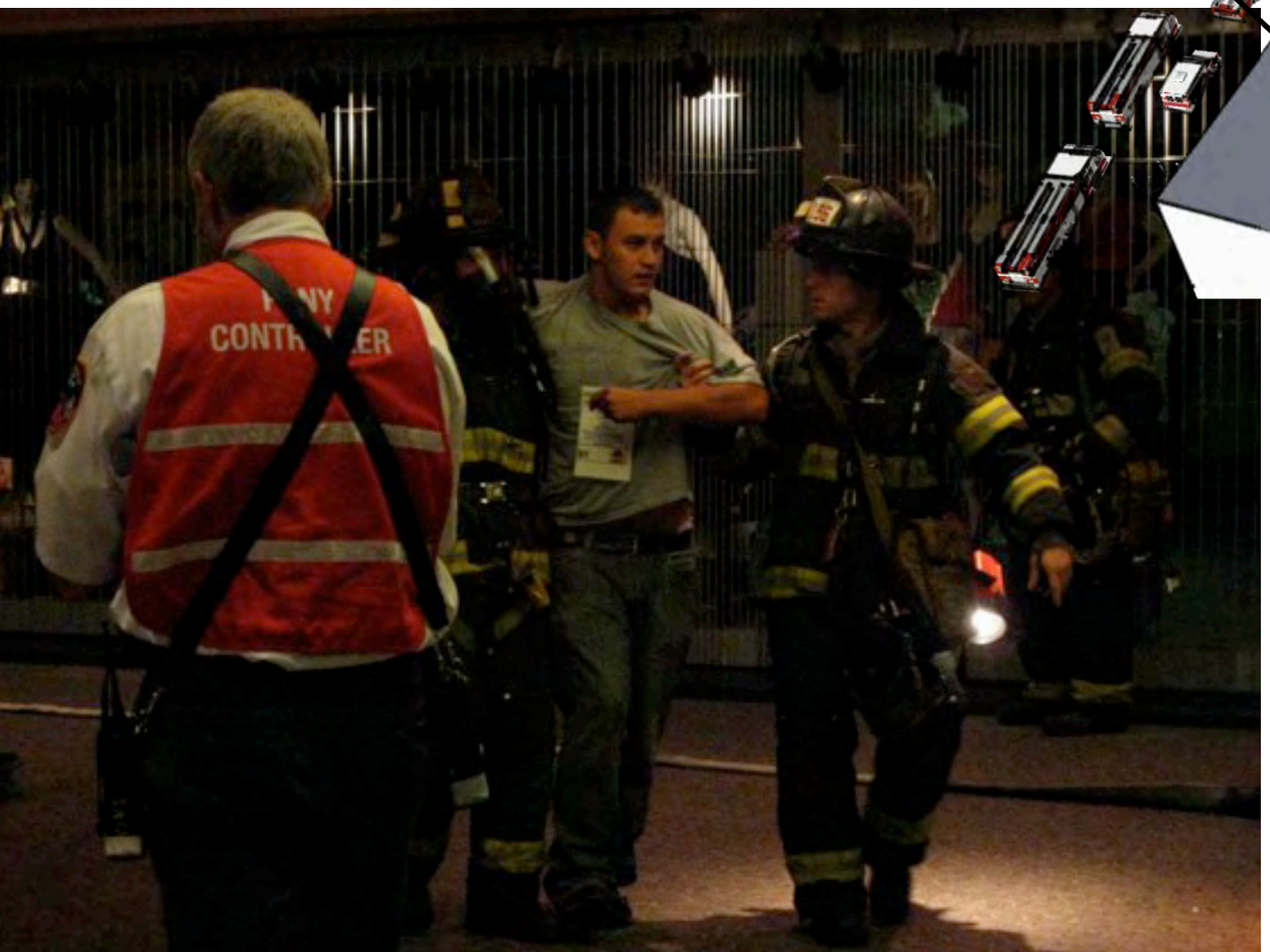
3. Getting stuck in outdated behaviors:

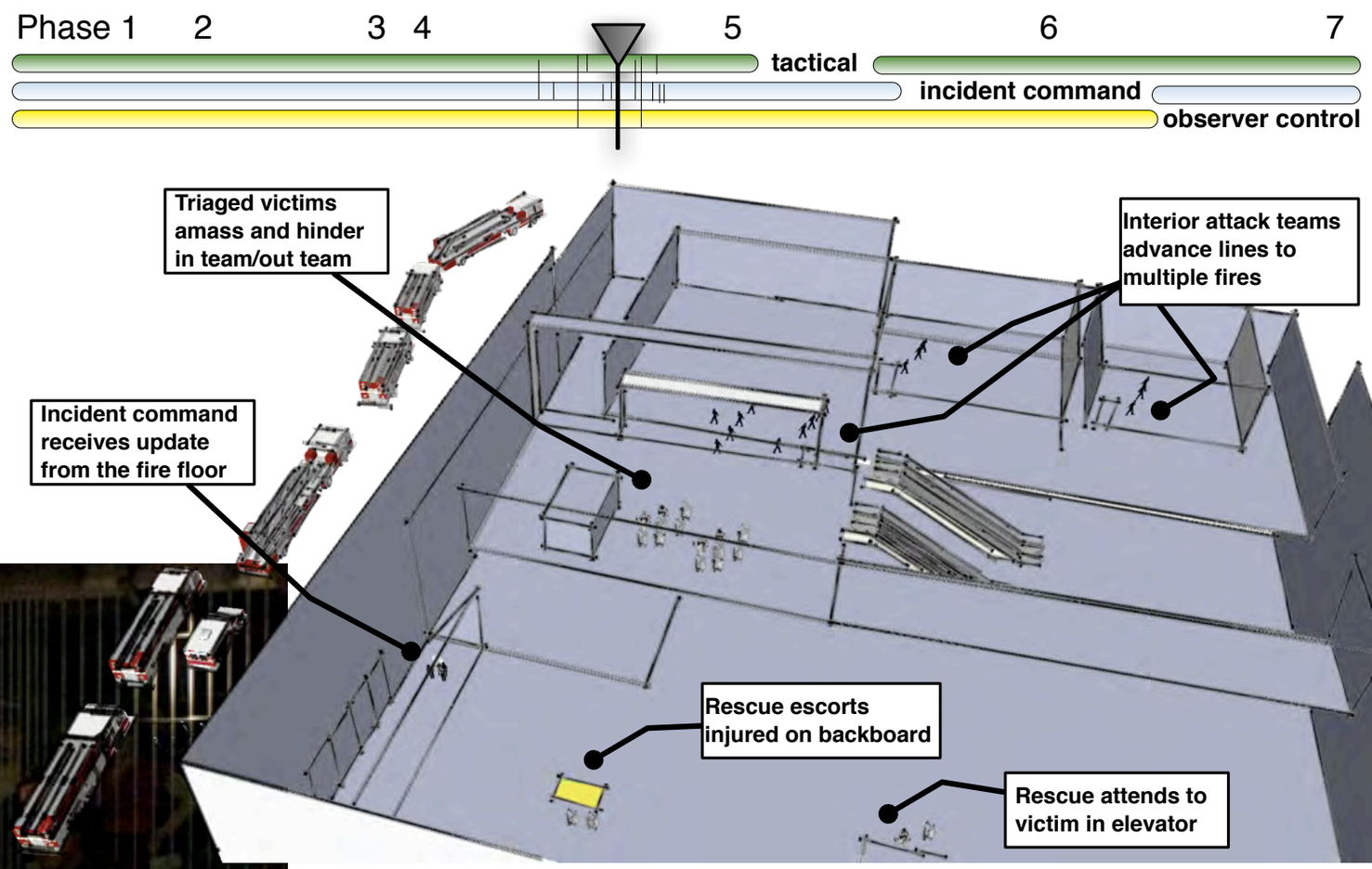
the world changes but the system remains stuck in what were previously adaptive strategies.

sub-patterns range over temporal and organizational scales

- Oversimplifications
- Failing to revise current assessment as new evidence comes in (Fixation)
- Failing to revise plan in progress when disruptions/ opportunities arise
- Discount discrepant evidence (eg, run up to Columbia)
- Literal Mindedness (automation failures)
- Distancing through differencing
- Cook's Cycle of Error

Urban Firefighting





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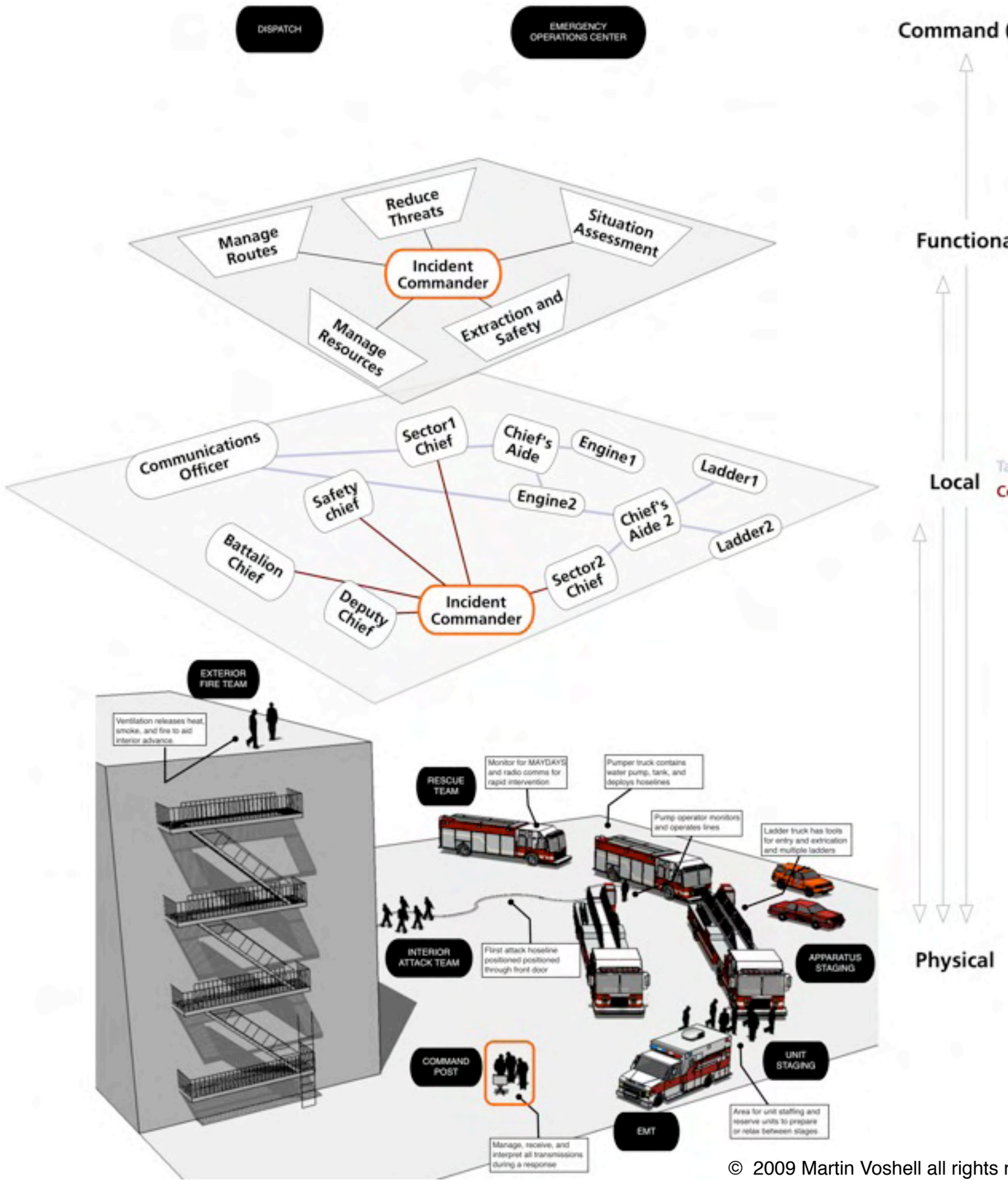
Urban Firefighting

~ distributed roles

~ multiple echelons

~ disrupting factors



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Wednesday, August 12, 2009

Crisis Management

~ multiple roles, multiple echelons, interdependent, all responsible

Strong Angel 3 test

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Maladaptive Patterns and Critical Incidents in Urban Firefighting
(Branlat et al., 2009)

Decompensation

- If request resources when need is definitive, it is already too late
- Regulate additional adaptive capacity (tactical reserves)
  ~ maintain margins of maneuver (ability to handle next surprise)
  ~ "avoid all hands situations" (incident command)
- Bumpy transfers of control

Working at cross-purposes (both horizontal and vertical)

- Actions of one group increase threats to other groups (opposing fire hoses; rendering escape routes or protected areas unaccessible)
- Failure to resynchronize
- Goal priorities/conflicts for response to distressed firefighter
- Tradeoff between information sharing versus data bottlenecks

Getting stuck in outdated behaviors

- Failures to modify plan in progress as situation changes

The Quest for Polycentric Control

multiple centers interdependent, each with partial authority and autonomy, all responsible, but differentially over goals

- empower decentralized initiative
  (at Sharp End Layer, up close roles)

- coordinate over emerging trends to meet priorities
  (Broad End Layer, distant 'supervisory' roles)

- these two layers are in constant interplay as situations evolve in themselves and as a result of activities at these levels

history:
cognitive psychology: Norman 1981/Rasmussen 1979
sociology: Ostrom 1999
military doctrine: commander's intent, Von Clauswitz
safety: Woods and Shattuck 2000; Cook et al., 2000
mission control:

Anticipation power (reflective/calibrated):

~ step outside current plan in progress/competence envelope to examine its changing fitness against emerging trends
~ dynamically managing appropriate **skepticism**
~ requires perspective shifts and contrasts

Hedges against Uncertainty

Suspicious: open to **re-**gather Managing Uncertainty

Skeptical: open to **re-**frame Managing Confidence

Progressive: open to **re-**plan Managing Commitment

Avoid hindsight trap:
the future in implausible; the past incredible

Synchronization power:

Cross checks: coordinate diverse and fresh perspectives

Anticipated responsiveness in the face of surprise
trust that other parts of the system will respond adaptively to disrupting events that alter plans and activities in progress

Anticipated Reciprocity
agent 1 shows “trust” for agent 2 by taking an action that gives up some amount of immediate benefit in return for a longer run benefit for both,

but in doing so agent 1 relies on agent 2 to “reciprocate“ in the future by taking an action that will give up some benefit to make both persons better off than they were at the starting point.

Distributed Accountability

A pilot prepares his descent into the destination airport and receives an initial ATC clearance for an instrument landing approach to runway 24 L together with a number of altitude constraints for various waypoints of the arrival. The pilot programs these constraints into the flight automation.
Shortly after the entire clearance has been programmed, an amended clearance is issued by ATC to now make an instrument landing approach to runway 24 R. (The change in runway was made because of an airport equipment failure.) When the pilot changes the runway in the instructions to the automation, the automation signals that it understands the runway change and begins to act based on this new target.

Question: Does the automation continue to use the altitude constraints which still need to be respected in this situation?

Is the automation suite responsive?

Radical Implications revisited:

All human adaptive systems, simultaneously, are
- well - adapted
- under - adapted
- mal - adapted

Tradeoffs are fundamental

Potential for surprise is ubiquitous

Adaptive behavior consumes success

The view from any single point of observation simultaneously reveals and obscures

In adaptive systems, yesterday's solutions produce today's surprises that become tomorrow's challenges.

Can we as stakeholders and problem holders monitor, learn, and modulate the adaptive capacities of the systems in which we function?